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14. ABSTRACT
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Report Title

Final Report: Nonequilibrium Floquet States in Topological Kondo Insulators

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This project aimed to design and implement an experiment intended to stabilize and test a newly proposed state of matter: the non-equilibrium Floquet topological metal. By performing electrical transport measurements while simultaneously propagating ultrasonic waves into the first known topological Kondo insulator, Samarium Hexaboride, we investigated the possibility of realizing a moving cascade of topological insulator-to-metal transitions to obtain bulk-like conduction through the Kondo insulator. Experiments in collaboration with Prof. T. Yanagisawa at Sapporo University, Japan, and Prof. T. McQueen at Johns Hopkins University resulted in a successful experimental observation of a positive effect. Further work is required to understand the origin of the anomalous effect of ultrasound propagation on electrical transport in SmB6.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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TOTAL:

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Received Paper

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Number of Presentations: 0.00

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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Received	Paper

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Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

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NAME	PERCENT_SUPPORTED
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Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Tyler Drye	0.25
FTE Equivalent:	**0.25**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Johnpierre Paglione	0.08	
Victor Galitski	0.08	
FTE Equivalent:	**0.16**	
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Names of Under Graduate students supported

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Names of Personnel receiving masters degrees

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NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

FINAL REPORT

BAA-12-R-0012 SHORT-TERM INNOVATIVE RESEARCH (STIR) PROGRAM
Agreement Number: W911NF-13-1-0227
Institutional Number: 09071492
Program Manager: M.D. Ulrich, Army Research Office

Title: *Nonequilibrium Floquet States in Topological Kondo Insulators*

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Summary:

This project aimed to design and implement an experiment intended to stabilize and test a newly proposed state of matter: the non-equilibrium Floquet topological metal. By performing electrical transport measurements while simultaneously propagating ultrasonic waves into the first known topological Kondo insulator, Samarium Hexaboride, we investigated the possibility of realizing a moving cascade of topological insulator-to-metal transitions to obtain bulk-like conduction through the Kondo insulator. Experiments in collaboration with Prof. T. Yanagisawa at Sapporo University, Japan, and Prof. T. McQueen at Johns Hopkins University resulted in a successful experimental observation of a positive effect. Further work is required to understand the origin of the anomalous effect of ultrasound propagation on electrical transport in SmB_6.

Background and Approach

This project brought together the concepts of the Topological Kondo Insulator (TKI) and Floquet dynamical systems to design and execute a targeted experimental study of a new proposed state: the non-equilibrium Floquet topological metal. The main idea relies on the knowledge that the low-temperature insulating state of SmB_6 is readily transformed to a metallic state by application of external pressure [Cooley 1995]. With low-temperature topological conduction occurring in SmB_6 due to the opening of the Kondo insulator gap at higher temperatures [Zhang 2013], this metallization likely occurs because the induced distortion of the lattice renormalizes the band structure where the Fermi level crosses over into the hybridization-induced "conduction band."

By propagating an elastic wave through a crystalline sample of SmB_6, the idea is to attempt to induce a moving cascade of such topological insulator-to-metal transitions thereby stabilizing a non-equilibrium topological metallic state that can be controlled using the parameters of the elastic wave propagation. An instantaneous snapshot of such a system would reveal segregated regions in the material where a topological insulator-to-metal transition is induced by the local strain field, yielding highly conducting layers in the sample akin to a bulk-like conduction state. We attempted this by using an ultrasound transducer to propagate phonon modes of controllable wavelength, amplitude and polarization, thereby locally inducing strained and expanded regions in the crystal of controllable spread, amplitude and direction. Through the manipulation of the polarization orientation of the propagating ultrasonic wave (ie. by attaching different cuts of $LiNbO_3$ piezo-electric transducers to the SmB_6 crystal) to change the direction of the propagating strain, the directional nature of the effect can be probed by comparing the resulting electrical conduction (measured simultaneously) in the presence of strain waves both parallel and perpendicular to the applied current direction. Any enhancement of conductance due to the non-equilibrium state should thus be controllably switched on or off by changing the polarization orientation, providing a simple yet thorough identification of the proposed phenomenon.

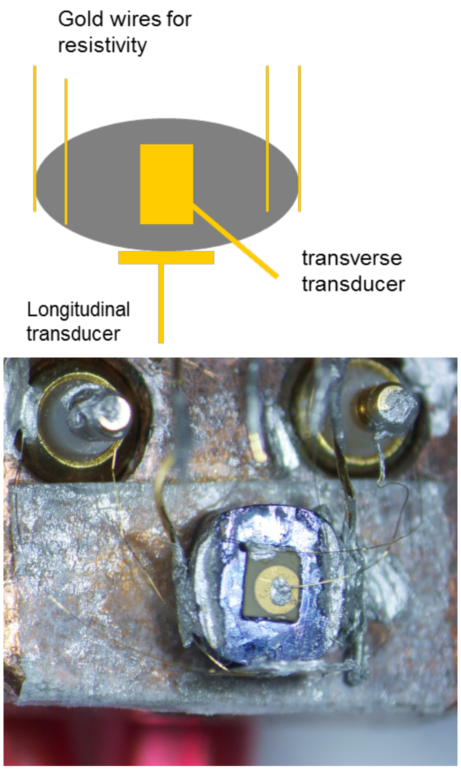

Figure 1: Experimental setup for simultaneous ultrasound/resistivity experiment on SmB_6 single crystal provided by T. McQueen, Johns Hopkins University.

Experimental Results

The experiment was designed in collaboration with Tatsuya Yanagisawa of the Goto ultrasound group in Sapporo, Japan, using standard $LiNbO_3$ piezoelectric transducers and a high-frequency vector network analyzer to both produce and measure ultrasonic wave propagation, while simultaneously measuring its electrical conduction with a four-wire contact geometry. The

experiment was performed at the base temperature of a He-3 cryostat (300 mK), where the TKI state is fully developed in SmB_6, using standard AC resistance bridge electronics.

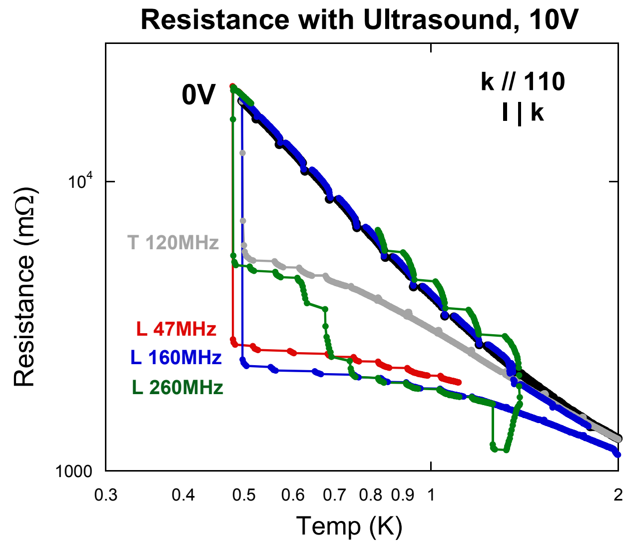

Figure 2: Longitudinal resistance measured in SmB_6 crystal with simultaneous ultrasound propagation. All curves taken with 10V transducer amplitude employed, with polarizations (T-transverse; L-longitudinal) and ultrasound frequencies indicated.

As shown in Figure 2, there is a notable effect of the ultrasound propagation on the measured electrical resistance below 2 K. This is an outstanding result if proven intrinsic, as it implies that propagation of ultrasonic waves induces a notable conductivity increase in an insulating crystal of SmB6. However, extrinsic heating effects are a potential source of the observation, which would act to reduce the absolute resistance at given bath temperature due to direct sample heating. In effect, if the sample temperature is much higher than the bath temperature, then the resistance will be reduced to match the value at that temperature in the nominal R(T) dependence without ultrasound applied.

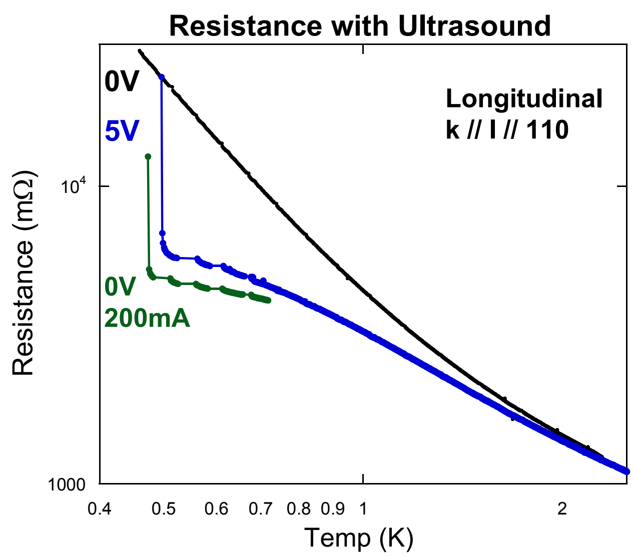

Figure 3: Joule heating tests for comparison to ultrasound-induced resistance reduction. Blue curve is resistance measured with very small excitation current and ultrasound amplitude set at 5 V. Green curve is resistance measured with intentionally large excitation current of 200 mA and no voltage on the ultrasound transducer.

While this is indeed possible, there are several reasons to believe that so-called "self-heating" is not taking place extrinsically. First, reflecting on years of experience in performing low-temperature ultrasound measurements on single-crystal samples, both the Sapporo and UMD groups agree that such a phenomenon has never been previously witnessed. This is easy to understand, as there are no electrical connections (or current flowing) in or to the sample in a typical ultrasound experiment, and the only energy being intentionally introduced is the mechanical energy of the transducer when energized and oscillating. Estimates of this energy place it far below any observable effect, even when such experiments are performed at lower temperatures in a dilution fridge (i.e. down to 20 mK). Second, we performed Joule heating tests to determine the amount of power required to mimic the presumed self-heating effect. As shown in Figure 3, one can indeed increase the excitation current of the resistivity measurement to mimic the reduction in resistance, but one needs to apply upwards of 200 mA (AC current, ~15 Hz) to mimic a 5 V transducer excitation. This translates to approximately 200 mW of power (given ~5 ohm sample

resistance), which is a significant amount of power that is required to overpower the cryostat cooling power and raise the temperature of the sample significantly (up to approximately 2 K). Therefore, we find it very difficult to explain the ultrasonic resistance reduction effect in SmB6 with an extrinsic self-heating explanation; there is simply no source of heater power sufficient to induce the observation with the given experimental conditions.

Future Work

The observation of a controllable non-equilibrium Floquet state would provide an immediate stepping stone to many other related ideas. Our initial observations hold great promise to be confirmed as a new phenomenon related to our aims in this project. Further work is required to better understand all potential sources of error in the experiment and the intrinsic nature of the observed phenomenon. This will require additional ultrasound experiments and systematic tests, including variations in transducer design and coupling, sample dependence, geometry dependence, and cryostat cooling power dependence. In addition, theoretical work is required to understand the energy landscape of ultrasound propagation in this material in the insulating state. All such activities are currently on hold until further funding is acquired to continue activities.

Finally, Galitski has predicted the effects of other perturbations, such as magnetic fields, that would easily find their place in follow-up work stemming from this project. The combination of theory and experiment follow-up for this project has potential to lead not only to the discovery of a new and very elegant physical effect predicted in this application, but also to the possible development of new devices. Because the conduction would naturally depend on the parameters of the perturbation, such as the wavelength and polarization for example, it potentially will allow precise control of the phenomenon. Depending on the sensitivity of the observed phenomenon, strain sensors based on the non-equilibrium Floquet topological metal may be conceivable. This would provide a completely new approach to sensitive strain detectors that may find niche applications of interest to the DoD.

References

J. C. Cooley, M. C. Aronson, Z. Fisk, P. C. Canfield, "SmB_6: Kondo Insulator or Exotic Metal?", Phys. Rev. Lett. 74, 1629 (1995).

X. Zhang, N. P. Butch, P. Syers, S. Ziemak, R. L. Greene, J. Paglione, "Hybridization, Inter-Ion Correlation, and Surface States in the Kondo Insulator SmB_6", Phys. Rev. X 3, 011011 (2013).